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SIMULATION, GENERATION, AND CHARACTERIZATION OF HIGH BRIGHTNESS ELECTRON SOURCE AT 1 GV/m GRADIENT*

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DISCLAIMER

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Abstract

This paper describes computer simulations and measurements on an electron bunch from a pulsed, high gradient gap. MAFIA and PBGUNS were used to calculate the emittance, brightness and energy spread of the electron beam for peak currents ranging from 10 A to 1 kA and pulse durations ranging from 0.3 ps to 10 ps. Under optimum conditions, normalized emittance of 10^{-7} π m-rad, beam brightness of $3\text{x}10^{15}$ A/(m-rad)^2 and energy spread of 0.15 % were obtained. A pulsed high voltage with 1 MV amplitude, and ~ 1 ns duration was applied to the diode with an interelectrode gap ranging from 2 mm to 0.5 mm. Copper cathodes with three different surface preparations, diamond polished, diamond turned and chemically cleaned, have been tested for their voltage hold-off properties under this high gradient and the Fowler-Nordheim plots were generated. The diamond polished OFC class II copper was shown to consistently produce lower dark current and higher hold-off voltage. Photoemission studies have been made using light from a KrF excimer. The field enhancement factor for photoemission was calculated to be 5, an order of magnitude smaller than the dark current beta for a similar surface.

1 SIMULATIONS

Two simulation codes, MAFIA and PBGUNS were utilized. Agreement between these codes has been demonstrated [1]. PBGUNS was then used to perform the bulk of the optimization, with only those issues that required time dependence being resolved with MAFIA.

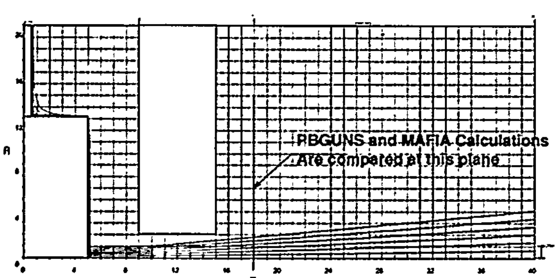

Fig 1. PBGUNS Geometry and particle trajectories

Figure 1 shows the standard geometry used in simulation. In all cases, output data from simulation was taken at 3.25 mm from the surface of the cathode. A 1 mm accelerating gap was used, with a potential of 1 MV on the cathode. The emitting spot had a radius of .25 mm and the initial transverse and longitudinal current densities were constant. Table 1 displays the emittance and brightness as a function of initial current and pulse duration, obtained using MAFIA results.

Current	Charge	Bunch length	Emittance	Brightness
A	nC	ps	π mm mrad	A/(mm^2mrad^2)
100	1	10	0.167	3571
100	0.3	3	0.088	12854
100	0.1	1	0.062	26014
100	0.03	0.3	0.073	18868
500	0.5	1	0.207	11668
250	0.25	1	0.132	14348
50	0.05	1	0.039	33557
10	0.01	1	0.045	5027

Table 1. 1-σ normalized slice emittance and brightness as a function of pulse duration and charge.

PBGUNS is a DC code and therefore does not provide information on longitudinal variation. Hence, slice emittance values were used in the optimizations to allow for a direct relationship with PBGUNS. The MAFIA results for the particle's r and p_r are used to calculate the 1-σ normalized slice emittance (using the center 1% of the beam for the emittance calculation), using the expression:

$$\varepsilon = 2\sqrt{\langle r^2\rangle\langle p_r^2\rangle - \langle r\cdot p\rangle^2} \qquad (1)$$

For the 100A, 10 ps case, the full beam 1-σ normalized emittance was found to be .385 π mm-mrad. The slice emittance for the center 1% of the beam under the same conditions was .167 π mm-mrad. It is important to note that the above results assume no random energy distribution at the source (such as might result from thermal effects or photon energy in excess of the work function). A random initial energy of 1eV places a lower bound of .17 π mm-mrad on the emittance, and leads to brightness of $3\text{x}10^{15}$ A/(m-rad)^2. Beyond 500A the transverse beam spreading due to space charge leads to clipping at the anode aperture.

PBGUNS has been used to investigate the effect of curving the cathode emission region to compensate for the divergence induced by the anode hole. Cathodes with radii of curvature of 1, 1.5 & 2 mm were used for a 100 A beam. It was found that by altering the cathode curvature, a collimated beam could be obtained or a focus could be provided at a desired location beyond the anode.

Simulations have also been done to study the longitudinal energy spread of the beam. Figure 2 shows a MAFIA plot of longitudinal position vs longitudinal momentum for a charge of 1nC and a pulse duration of 10 ps. The RMS energy spread is .15%.

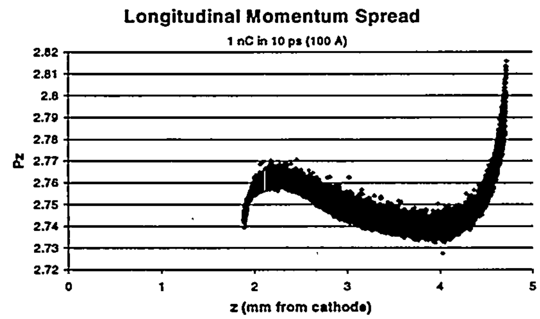

Fig 2. Charge induced longitudinal momentum spread. Pz is in $\beta_z\gamma$.

MAFIA was also used to investigate the longitudinal variation of the transverse emittance. Figure 3 shows the r vs r' curves for three 1% slices taken from the front, middle and back of a 10ps bunch, all at 3.25 mm from the cathode.

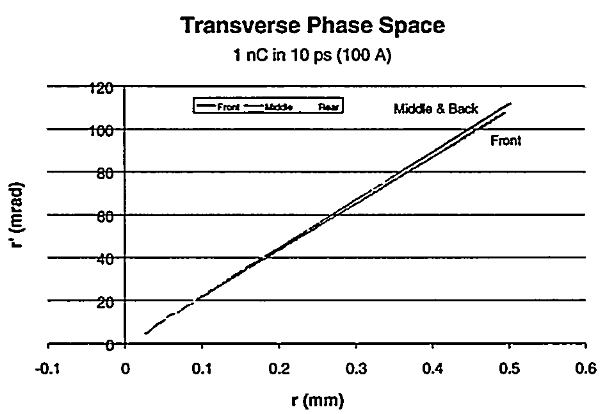

Fig 3. Longitudinal variation of the transverse phase space.

2 EXPERIMENTAL RESULTS

2.1 Dark Current

One advantage of a pulsed power gun is the ability to maintain higher field gradients. Experiments have shown that higher breakdown thresholds of materials can be obtained under short pulse conditions as compared to DC [2]. With our generator pulsed voltages up to 1 MV with a 1 ns duration can be applied to diodes with interelectrode spacing ranging from 2-0.5 mm. Details of the pulse generator and the experimental arrangement can be found elsewhere[3]. The dark current and maximum field before breakdown were measured for chemically cleaned (prepared using SLAC specification C01a.1 without steps 8-9), single point diamond turned and diamond polished (preparation described in [4]) OFC copper cathodes.

The cathodes were installed in a vacuum gap with 1.5 mm interelectrode spacing. The voltage amplitude on the cathode was slowly increased from 300 kV to 800 kV, allowing the cathode to condition. The field on the conditioned cathode was then gradually reduced. The dark current from the cathode, collected on a faraday cup positioned 5 mm from the cathode, is then measured as a function of the applied voltage. The gap was then reduced to 1 mm and the process was repeated. The criterion for breakdown was assumed to be a sudden, irrevocable increase in the dark current accompanied by a visible flash. A Fowler-Nordheim[5] plot was generated using the data prior to breakdown for the chemically cleaned cathode (1.5 mm interelectrode spacing) and the diamond polished cathode (1 mm and 1.5 mm spacing). The field enhancement factor, β, has been calculated for each case, assuming a cathode work function of 4.65 eV[6]. For the diamond turned sample, the surface could not be conditioned using the standard technique, and no dark current measurements were taken for this sample. The field enhancement factor β for chemically cleaned copper, conditioned to ~500 MV/m was measured to be 76. β for the diamond polished sample under similar conditions was 46. The same sample when conditioned up to 800 MV/m field had an enhancement factor of 30. This reduction in β from a 1.5 mm to 1 mm electrode spacing for the polished sample is likely an effect of the conditioning process.

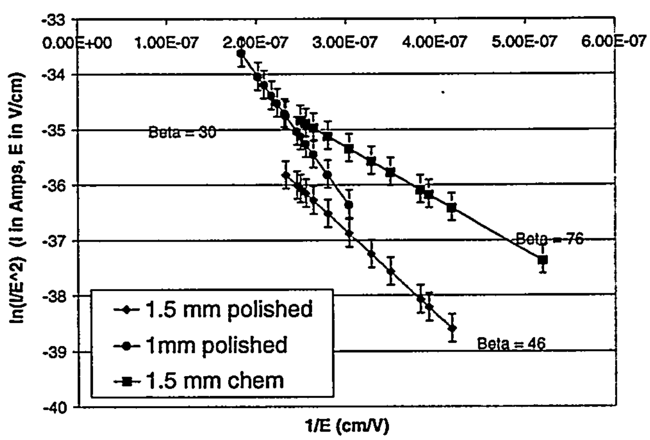

Fig 4. Fowler Nordheim plot for chemically cleaned and diamond polished Cu cathodes.

Both the chemically cleaned and diamond turned samples suffered breakdown when the electrode spacing was set to 1mm, and both had significantly higher currents. Of the three surface preparation methods tested, diamond polish seemed to have a lower dark current and higher hold-off voltage. A similarly prepared surface was tested to hold-off field gradients up to 1.66 GV/m [1]. Further increase in the field was limited by our experimental arrangement.

2.2 Photocurrent

Photoemission measurements have been made by illuminating the cathode with light form a KrF excimer (248 nm, photon energy of 5 eV) laser. The laser spot illuminated the center 1 mm diameter of the cathode at normal incidence. The interelectrode spacing was set at 2 mm, and voltage amplitudes from 200kV to 500 kV were applied to the cathode coincident with the laser pulses. The cathode was diamond polished, and was conditioned to 250 MV/m. The emitted charge was then collected on the Faraday cup in the same manner as the dark current. At these applied fields, the dark current was negligible and did not contribute to the photocurrent. Collected charge was measured as a function of laser energy and voltage amplitude. The laser pulse duration was 23 ns FWHM, much longer than the voltage pulse duration of 1 ns. For this measurement, the pulser was run in self-triggered mode leading to a jitter with respect to the laser of 20 ns. Only those shots falling into a 3 ns window at the peak of the laser pulse are considered in this analysis. The charge collected was found to have a linear dependence on the laser energy for a constant applied voltage. This finding is in agreement with the expected dependence for a laser with a photon energy greater than the work function of the copper cathode (4.65 eV), in the space charge free regime.

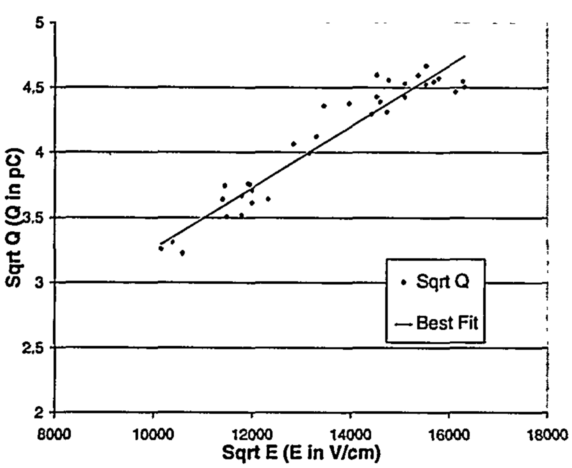

Fig 5. Sqrt of applied field vs Sqrt of measured charge (corrected for variation in laser energy). The slope is 2.35e-4 and intercept is .915.

In the presence of an applied field, the charge emitted from the cathode can be written as [5]:

$$Q = A(h\nu-\phi+\alpha(\beta E)^{1/2})^2$$

Here A is a constant of proportionality which includes the laser energy, $\alpha=(e/4\pi\varepsilon_0)^{1/2}$, $h\nu$ is the photon energy, ϕ is the work function, E is the applied field and β is the field enhancement factor of the surface for photoemission. Figure 5 shows a plot of $E^{1/2}$ vs $Q^{1/2}$ for constant laser energy. The ratio of the slope to the intercept is then:

$$\text{Slope/intercept} = \alpha(\beta)^{1/2}/(h\nu-\phi)$$

For a work function of 4.65 eV, the slope and the intercept obtained from Figure 5 result in a field enhancement factor of 5 for photoemission, significantly smaller than that for the dark current. The origin of this difference is not yet fully understood. More systematic analysis of the photoemission data and measurement of dark current from this surface under higher applied fields are currently underway to help better understanding.

3 CONCLUSION

Simulations have been performed to study the beam parameters at the output of a 1 MeV pulsed power gun. It was found that emittance of .2 π mm-mrad and brightness of 3×10^{15} A/(m-rad)^2 were predicted, with an energy spread of 0.15% for a 100A beam with 10 ps pulse duration.

Measurements of dark current have been made on copper cathodes with three different surface preparations. The behavior of the polished sample was significantly superior in terms of lower dark current and higher breakdown threshold. Field enhancement values for field emission were measured to be ~30 for the polished surface and 76 for the chemically cleaned surface.

Measurements of photocurrent were performed with a KrF excimer. The emitted charge was measured to be linear with the laser energy. Dependence of the charge on the applied field indicate a field enhancement factor of 5 for photoemission, significantly lower than the dark current field enhancement factor for a similar surface.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

[1]T. Srinivasan-Rao, et al, presented at 8th Workshop on Advanced Accelerator Concepts, , Baltimore, MD, 6-11, July (1998)

[2] G. A. Mesyats and D. I. Proskurovsky, Pulsed Electrical Discharge in Vacuum, (Springer-Verlag, 1989), p.109

[3]T. Srinivasan-Rao, J. Smedley, Advanced Accelerator Concepts workshop, AIP Conference Proceedings 398, NY 1997, P. 730.

[4] T. Srinivasan-Rao, J. Yu, X. J. Wang, BNL report 62626, Brookhaven National Lab, (1996)

[5]M. Cardona and L. Ley, Photoemission in Solids I, (Springer-Verlag., 1978), pp. 21-29

[6]CRC Handbook of Chemistry and Physics, edited by R. C. Weast, (CRC Press, Inc, 1984), pg. E-76